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# Does the interstellar magnetic field follow the Chandrasekhar-Fermi law?

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**Abstract.** We carried out 1.25 pc resolution MHD simulations of the ISM – including the large scale galactic fountain – by fully tracking the time-dependent evolution of the magnetic field and the formation of shock compressed regions in a supernova-driven ISM. The simulations show that large scale gas streams emerge, driven by SN explosions, which are responsible for the formation and destruction of shocked compressed layers with lifetimes up to some 15 Myr. The T$\leq 10^3$ K gas is distributed in filaments which tend to show a preferred orientation due to the anisotropy of the flow induced by the galactic magnetic field. The simulations also show that the magnetic field has a high variability, it is largely uncorrelated with the density and it is driven by inertial motions. The latter is consistent with the fact that ram pressure dominates the flow for $10^2 <$T$\leq 10^6$ K. For T$> 10^6$ K thermal pressure dominates, while for T$\leq 10^2$ K (stable branch) magnetic pressure takes over.

**Key words:** Magnetohydrodynamics – Galaxy: disk – ISM: general – ISM: kinematics and dynamics – ISM: structure

## 1. INTRODUCTION

Recent work by Kim et al. (2001) and Passot & Vázquez-Semadeni (2003) show somewhat contradicting results on the scaling of the magnetic field with density in the ISM. Kim et al. using a (200 pc)$^3$ box centered in the Galactic midplane with periodic boundary conditions, driven by SNe at a rate of 12 times the Galactic value and using an uniform field strength of 5.8 $\mu$G orientated along the $x-$direction, claim that the magnetic field scales as $\rho^{0.4}$ at densities

$n > 1$ cm$^{-3}$, although their Fig. 2 shows an almost order of magnitude variation in the field for the same density. On the other hand Passot & Vázquez-Semadeni show that for small Alfvénic Mach number the magnetic field is uncorrelated with density, exhibiting a large scatter, which decreases towards higher densities.

In this paper we investigate the variability of the magnetic field in the Galactic disk and its correlation with the density in global MHD simulations of the ISM, driven by SNe occuring at the Galactic rate. Other important issues like the volume filling factors of the ISM "phases", the dynamics of the galactic fountain, the conditions for dynamical equilibrium and the importance of convergence of these results with increasing grid resolution have been treated elsewhere (Avillez 2000, Avillez & Breitschwerdt 2004a, b).

## 2. MODEL AND SIMULATIONS

We ran kpc-scale MHD simulations of the SN-driven ISM on a cartesian grid of $0 \leq (x, y) \leq 1$ kpc size in the Galactic plane and $-10 \leq z \leq 10$ kpc into the halo with a finest adaptive mesh refinement resolution of 1.25 pc, using a modified version of the 3D model of Avillez (2000). The new model allows for the motion of OB associations and includes magnetic fields (Avillez & Breitschwerdt 2004b). At the beginning of the simulations the uniform field components along the three axes are given by $(B_{u,0}(n(z)/n_0)^{1/2}, 0, 0)$, where $B_{u,0} = 3\,\mu$G is the field strength, $n(z)$ is the number density of the gas as a function of distance from the Galactic midplane and $n_0 = 1\,\mathrm{cm}^{-3}$ is the average midplane density. The random field component is set to zero in the beginning of the simulations. This component is built up during the first millions of years of evolution as a result of turbulent motions, mainly induced by SN explosions.

## 3. RESULTS

### *3.1. Global Evolution*

The initial evolution of the magnetized disk is similar to that seen in purely HD runs (Avillez 2000, Avillez & Breitschwerdt 2004a), that is, the initially stratified distribution does not hold for long as a result of the lack of equilibrium between gravity and (thermal, kinetic and turbulent) pressure during the "switch-on phase" of SN

Left panel: mavillez_fig1a, Right panel: mavillez_fig1b

**Fig. 1.** Density and magnetic field distribution in the Galactic midplane after 374 Myr of evolution. The resolution of the finest AMR level is 1.25 pc.

activity. As a consequence the gas in the upper and lower parts of the grid collapses onto the midplane, leaving low density material in its place. However, in the MHD run it takes a longer time for the collapse to be completed as a result of the opposing magnetic pressure and tension forces. As soon as the system has collapsed and enough supernovae have gone off in the disk building up the required pressure support, transport into the halo is not prevented, although the escape of the gas takes a few tens of Myr to occur. The crucial point is that a huge thermal overpressure due to combined SN explosions can sweep the magnetic field into dense filaments and punch holes into the extended warm and ionized HI layers. Once such pressure release valves have been set up, there is no way from keeping the hot over-pressured plasma to follow the pressure gradient into the halo. As a consequence the duty disk-halo-disk cycle of the hot gas is fully established, in which the competition of energy input and losses into the ISM by SNe, diffuse heating, radiative cooling and magnetic pressure leads the system to evolve into a dynamical equilibrium state within a few hundred Myr. This time scale is considerably longer than that quoted in other papers (e.g., Korpi et al. 1999, Kim et al. 2001), because in these the galactic fountain has not been taken into account.

Fig. 1 shows slices of the 3D data cube of the density and magnetic field distributions in the Galactic midplane. The highest density gas tends to be confined to shocked compressed layers that form

in regions where several large scale streams of convergent flow (driven by SNe) occur. The compressed regions, which have on average lifetimes of 10-15 Myr, are filamentary in structure, tend to be aligned with the local field and are associated with the highest field strengths. The formation time of these high density structures depends on how much mass is carried by the convergent flows, how strong the compression is and on the rate of cooling of the regions under pressure.

### *3.2. Field Variability and Dependence with Density*

During the evolution of the system, thermal and dynamical processes broaden the distribution of the field strength in such a way that after the global dynamical equilibrium has been set up the field strength in the disk spans two orders of magnitude from $10^{-7}$ to $10^{-5}$ G (Fig. 2). The figure shows a *large* scatter in the field for the same density suggesting that the field is being driven by the inertial motions, rather than it being the agent determining the motions. In the latter case the field would not be strongly distorted, and it would direct the motions predominantly along the field lines. The high field variability is also seen in the right panel of Fig. 1, which shows a highly turbulent field, that seems to be uncorrelated with the density, and thus, the classical scaling law $B \sim \rho^{\alpha}$, with $\alpha = 1/2$, according to the Chandrasekhar-Fermi (CF) model (1953) will not hold. It should be kept in mind that in CF it was assumed that the field is distorted by turbulent motions that were subalfvénic, whereas in our simulations in addition both supersonic and superalfvénic motions can occur, leading to strong MHD shocks. It now depends if the density fluctuations are primarily caused by thermal and/or ram pressure fluctuations and therefore being uncorrelated with the magnetic field, or if MHD waves

mavillez_fig2.jpg

**Fig. 2.** Scatter plot of B vs $\rho$ for the T$\leq 10^3$ (black), $10^3 <$T$\leq 10^4$ (green), $10^4 <$T$\leq 10^{5.5}$ K (blue) and T$> 10^{5.5}$ K (red) regimes at 400 Myr of disk evolution.

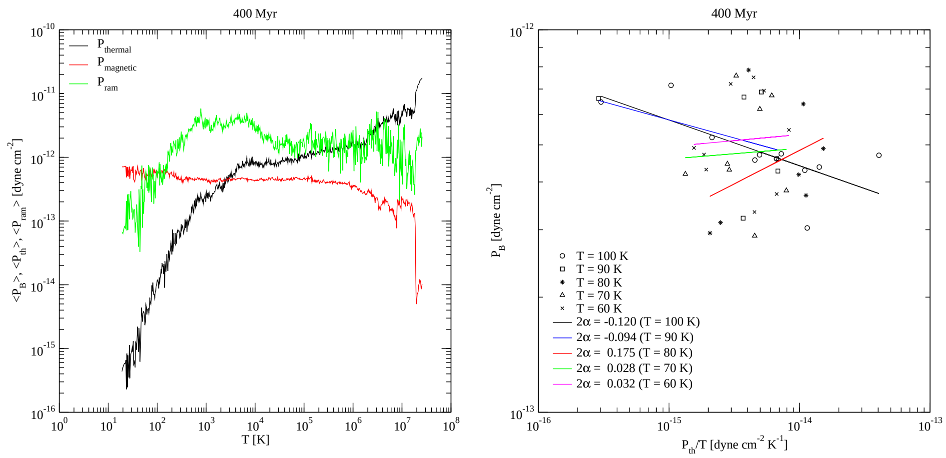


**Fig. 3.** The left panel shows the average magnetic (red), thermal (black) and ram (green) pressures as functions of temperature at 400 Myr. The right panel shows the variation of $P_B$ with $P_{th}/T$ for $T< 10^2$ K gas in the disk. The $2\alpha$ parameters are the slopes of the straight lines and correspond to the relation $P_B \propto (P_{th}/T)^{2\alpha}$ if a $B \propto \rho^{\alpha}$ law is assumed.

are the driving agent and provide a coupling between matter and field. Therefore, in general $0 \leq \alpha \leq 1$ would be expected. However, it should be noted that in reality heating and cooling processes, and even magnetic reconnection could induce further changes. Observationally there seems to be some evidence from measuring magnetic field strengths in the cold neutral medium, that $B$ and $\rho$ can be largely uncorrelated (Troland & Heiles 2001).

The left panel of Fig. 3 shows that the $T\leq 10^2$ K gas has $P_B > P_{ram} \gg P_{th}$, demonstrating that magnetically dominated regions do exist, while the $T> 10^6$ K gas has the highest thermal pressure and the lowest magnetic pressure. For $T< 10^2$ K the relation $B \propto \rho^{\alpha}$ does not hold either, as $\alpha$ varies between -0.006 and 0.085 (right panel of Fig. 3) suggesting that the thermal and magnetic pressures are independent. This result is largely consistent with the almost zero variation of magnetic pressure with temperature seen in the left panel of Fig. 3. For $10^2 <T< 10^6$ K ram pressure determines the dynamics of the flow, and therefore, the magnetic pressure does not act as a restoring force (Passot & Vázquez-Semadeni 2003) as it was already suggested by the lack of correlation between the field strength and the density. Fig. 3 also shows that the basic assumption of energy equipartition, made in the paper by CF (1953) in order to calculate

the magnetic field in the spiral arm, is clearly not fulfilled.

## 4. DISCUSSION

The dynamical picture that emerges from these simulations is that thermal pressure gradients dominate mostly in the neighborhood of SNe, which drive motions whose ram pressures are dominant over the mean thermal pressure (away from the energy sources) and the magnetic pressure. The magnetic field is only dynamically important at low temperatures, but can also weaken gas compression in MHD shocks and hence lower the energy dissipation rate. The thermal pressure of the freshly shock heated gas exceeds the magnetic pressure by usually more than an order of magnitude and the B-field can therefore not prevent the flow from rising perpendicular to the galactic plane. Thus hot gas is fed into the galactic fountain at almost a similar rate than without field.

The present simulations do not include self-gravity, which could have an important effect on high density regions, although on the verge of Jeans instability these would decouple from the ambient ISM flow. Moreover heat conduction has been neglected in the view of it being second order in comparison to the dominance of bulk motions and turbulent mixing. In the spirit of building a bottom-up model of the ISM further components (e.g., cosmic rays) and processes (e.g., non-equilibrium cooling) will be included in future simulations.

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## REFERENCES

**??**villez M. A. 2000, MNRAS, 315, 479

**??**villez M. A., Breitschwerdt D. 2004a, A&A, in press

**??**villez M. A., Breitschwerdt D. 2004b, Ap&SS, in press (astro-ph/0310634)

**??**handrasekhar S., Fermi E. 1953, ApJ, 118, 113

**??**errière K. M. 1998, ApJ, 503, 700

**??**im J., Balsara D., Mac Low M.-M. 2001, JKAS, 34, S333

**??**orpi M. J., Brandenburg A., Shukurov A., Tuominen I., & Nordlund A. 1999, ApJ, 514, L99

**??**assot T., Vázquez-Semadeni E. 2003, A&A, 398, 845

**??**roland T. H., Heiles C., 2001, BAAS, 33, 918